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Three-dimensional correction of distal radius intra-articular malunions using patient-specific drill guides

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Abstract: **PURPOSE:** To analyze the feasibility of combining computer-assisted 3-dimensional planning with patient-specific drill guides and to evaluate this technology's surgical outcomes for distal radius intra-articular malunions. **METHODS:** Six symptomatic patients with intra-articular malunions of the distal radius with a stepoff of more than 2 mm were treated with an outside-in corrective osteotomy. The described cases consist of 2 malunited volar Barton fractures, 2 radial styloid fractures, 1 AO-type C1 fracture, and 1 die-punch fracture. The osteotomies were guided by 3-dimensionally generated aiming guides that allowed precise cutting and the reduction of up to 2 fragments. All 6 patients were examined clinically and radiologically after 1 year. The surgical outcomes were quantitatively analyzed by comparing the preoperative and postoperative computed tomographic data. **RESULTS:** In all 6 cases, the osteotomies were consolidated 8 weeks postoperatively. After 1 year, 4 patients were pain-free, 1 had mild pain, and 1 experienced moderate pain during heavy work. Wrist motion and grip strength were improved in all patients. The postoperative radiographs showed no articular stepoff or degenerative changes. **CONCLUSIONS:** Patient-specific aiming guides provided a reliable method to correct intra-articular malunions of the distal radius. This technique allows the surgeon to safely perform difficult intra-articular osteotomies and may help limit the need for salvage procedures such as partial or complete wrist arthrodesis.

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Abstract

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To analyze the feasibility of combining computer-assisted 3-dimensional planning with patient-specific drill guides and to evaluate its surgical outcomes for distal radius intra-articular malunions.

Methods:

Six symptomatic patients with intra-articular malunions of the distal radius with a step-off of more than 2 mm were treated with an outside-in corrective osteotomy. The described cases consist of 2 malunited volar Barton fractures, 2 radial styloid fractures, one AO-type C1 fracture, and 1 die-punch fracture. The osteotomies were guided by 3-dimensionally generated aiming guides that allowed precise cutting and the reduction of up to 2 fragments. All 6 patients were examined clinically and radiologically after 1 year. The surgical outcomes were quantitatively analyzed by comparing the pre- and postoperative computed tomographic data.

Results:

In all 6 cases, the osteotomies were consolidated 8 weeks postoperatively. After 1 year, 4 patients were pain-free, one had mild pain, and one experienced moderate pain during heavy work. Wrist motion and grip strength were improved in all patients. The postoperative radiographs showed no articular step-off or degenerative changes.

Discussion:

Patient-specific aiming guides provided a reliable method to correct intra-articular malunions of the distal radius. This technique allows the surgeon to safely perform difficult intra-articular osteotomies and may help limit the need for salvage procedures such as partial or complete wrist arthrodesis.

Level of Evidence: IV, therapeutic studies

INTRODUCTION

Malunion of intra-articular distal radius fractures with a step-off of more than 2 mm may lead to radiocarpal degeneration¹. Posttraumatic degenerative arthritis can cause pain and may result in reduced range of motion and decreased grip strength²⁻⁴. Ultimately, salvage procedures (e.g., arthrodesis), which inevitably and irreversibly cause loss of wrist motion and strength, may be necessary. The avoidance of salvage surgeries may justify even a complex intervention, such as an intra-articular corrective osteotomy. Several case series have shown that correction of intra-articular malunion improves function, decreases pain, and may retard degenerative change⁵⁻⁷. However, in all reported cases, the joint had to be opened to perform the osteotomy and control the reduction. In contrast, del Pinal and colleagues⁸ reported 4 cases in which an arthroscopically assisted inside-out technique was applied. Such an approach, in which the joint capsule of the wrist is left intact, may increase the postoperative range of motion and may theoretically inflict less damage to the blood supply of the cut bone. Oka et al.⁹ reported 1 patient who was treated with an extra-articular, outside-in approach that also allowed the osteotomy to be performed without opening the joint. Additionally, this technique enables fragments that are located on the palmar aspect of the distal radius to be accessed. Their method relies on computer-assisted preoperative 3-dimensional (3D) planning and individualized drill guides for intraoperative support.

We report on the further development of the technique described by Oka et al.⁹ and present 6 cases of intra-articular malunion of the distal radius that were successfully treated by a palmar, dorsal, or combined approach with the mobilization of up to 2 fragments. In all of the cases, computer-assisted preoperative planning was performed, and patient-specific drill guides were designed, manufactured, and used for the procedure.

MATERIAL AND METHODS

Between February 2008 and January 2012, we treated 6 consecutive patients with intra-articular malunions of the distal radius. Approval from the responsible ethics committee and informed patient consent were obtained. Prior to presentation at our institution, all patients except case 4 (previous osteosynthesis) had nonoperative treatments. Crepitus in the radiocarpal joint and pain with loading and movement

were present in all patients. The range of motion and strength were quantified using a goniometer and a Jamar dynamometer, respectively. Table 1 summarizes the preoperative measurements.

Computed tomographic (CT) data (120 kV, Philips Brilliance 40 CT, Philips Healthcare, Netherlands) were used to generate 3D triangular surface models of the patient's radiuses by segmenting the bone anatomy using commercially available software (Mimics, Materialise, Belgium). In case 1, only the concerned radius was imaged. For all other cases, CT scans of both wrists were acquired to use the contralateral uninjured radius as the reconstructive template. The axial resolution of the CT data was 1 mm.

Based on these data, the surgery was virtually planned on a standard personal computer using in-house developed software. The model of the contralateral radius was mirrored and superimposed on the malunited bone. Thereafter, the fracture lines and articular step-off were defined to construct the osteotomy planes. Multiple osteotomy planes were required for cutting and mobilizing the fragment. The osteotomy planes were set according to the accessibility of either the dorsal or volar aspect of the distal radius. Additionally, the direction in which the fragment had to be shifted was taken into account. If rotation of the fragment was also required, a wedge of bone had to be either removed or inserted.

Next the drill guides were designed. Virtual drill holes spaced at 5 mm were placed along the osteotomy planes and extended with barrel-shaped drill-sleeves. The length of these sleeves was carefully matched to the length of the drill bit to avoid entering the radiocarpal joint. Depending on the drill bit length, holes with a diameter of either 1.2 mm or 1.5 mm were used. The drill tubes were then combined with a user-defined drill guide that was molded to conform to the bone surface. The irregular bone surface around the osteotomy helped uniquely identify the position on the bone where the guide would be placed during the surgery. To this end, the bone surface model was subtracted from the guide model.

Our first case was planned in collaboration with Prof. F. Stockmans (Leuven, Belgium), who already had experience with this technique. All other cases were exclusively planned by the surgeon who performed the intervention. The patient-specific drill guides were manufactured by Materialise (Leuven, Belgium) and Medacta (Castel San Pietro, Switzerland) using selective laser sintering. The guides

were made from polyamide (PA-12) and sterilized with conventional steam pressure sterilization.

During the surgery, the bone upon which the guide was intended to be placed was accessed with a dorsal, volar, or combined approach. The periosteum and other soft tissues were debrided to allow a unique fit of the guide. Once the guide was applied to the surface of the bone, the holes were drilled, a K-wire was inserted into the holes, and a cannulated chisel was used to connect the holes to complete the osteotomy.

Case 1

This 63-year-old retiree had a volar-radial to dorsal-ulnar fracture line (AO 23-B1.2). As shown in Figure 1, a proximal shift of the scaphoid fossa of nearly 3 mm was present. The correct position of the fragment was restored by shifting it distally along the osteotomy surface (Figure 2). The fixation was performed with a 2.4 mm LCP Distal Dorsal Radius L-plate (Synthes, Solothurn, Switzerland).

Case 2

This 39-year-old man had a volar Barton fracture (AO 23-B3.2), resulting in a 2.5 mm proximally shifted fragment (Figure 2). A volar approach was performed to position the guide at the volar ulnar aspect of the distal radius. Thereafter, the fragment position was corrected by shifting it along the V-shaped osteotomy plane in the distal direction. The fixation was performed with a 2.4 mm LCP Distal Radius L-plate (Synthes).

Case 3

This 49-year-old woman had a malunion of a volar Barton fracture (AO 23-B3.2). The malunited part was displaced in a proximal and palmar direction. Figure 2 depicts the 3D planning of the closing wedge osteotomy. A single drill guide was used to define the bi-planar osteotomy planes of the wedge. The fixation was performed with a modified 2.4 mm LCP Volar Distal Radius plate (Synthes).

Case 4

This 52-year-old woman had a sagittally oriented fracture line with a depression of the scaphoid fossa fragment (AO 23-C1.2). In addition to an intra-articular step-off of 3 mm, a gap of several millimeters was present at the dorsal side of the radius resulting in a pronation deformity. A combined dorsal and volar approach was planned using drill guides from both sides, as shown in Figure 2. The dorsal V-shaped plane allowed the correction of the pronation deformity by resecting a wedge. Furthermore, an extra-articular osteotomy was required to correct the radial length and inclination of the joint, which was guided in a similar manner to that described earlier¹⁰. The fixation was performed with a 2.4 mm LCP Distal Radius T-plate (Synthes).

Case 5

This 33-year-old man had a burst fracture (AO 23-B2.2) resulting in displaced volar-radial and dorso-radial fragments. We combined a dorsal and volar approach supported by 2 drill guides. For correction of the dorsal fragment, a distal shift along the V-shaped osteotomy plane was performed, as demonstrated in Figure 2. The malrotation of the volar fragment was corrected by removing a large bone wedge consisting of 3 osteotomy planes. The fixation was performed using a 2.4 mm Distal Radius L-plate (Synthes) volarly and 2 2.4 mm single compression screws dorsally (Synthes).

Case 6

This 51-year-old man had a die-punch fracture with a centrally depressed and rotated fragment (AO 23-B2.2) on the ulnar side of the scaphoid fossa. We accessed the central fragment dorsally, as shown in Figure 2. First, a V-shaped osteotomy was performed, and the resulting dorsal fragment was flipped distally while leaving the joint capsule intact. The central fragment was mobilized by cutting through 3 osteotomy planes under direct view and by applying a fifth cut from the radial side (coronal plane). Thereafter, the fragment was elevated, and the resulting gap was filled with cancellous bone obtained from the Lister tubercle. Lastly, the dorsal fragment was replaced in its initial position. The fixation of the fragments was performed with 3 single compression screws, each having a diameter of 2.0 mm (Synthes).

Evaluation Method

All patients had intraoperative fluoroscopy and postoperative CT scans. The patients had a clinical and radiological follow-up at 1 year after the surgery. In addition to the clinical evaluation, 3D-based quantification of the step-off and rotational errors was conducted. Manually defined surface patches were selected for each fragment as depicted in Figure 3. The patches were selected on the articular surface of the preoperative, contralateral, and postoperative CT scans. For patient 1, who was missing the contralateral CT, the 3D model of the desired planning result was used instead. A linear regression model¹¹, i.e., the optimal 3D plane in a least-squares sense¹², was calculated from all 3D points of the patch (Figure 3). Then the articular displacement error d between 2 configurations was chosen as the average distance (i.e., the root mean square error¹¹) from all points of 1 patch to the plane of the other patch. As depicted in Figure 3, the goal of the applied measure was to estimate the intra-articular step-off 3-dimensionally while not solely relying on a single manual measurement. The step-off was quantified for each fragment in the preoperative and contralateral configurations, d_{pre} and compared with the displacement, d_{post} in the postoperative and contralateral configurations. In the presence of a malrotation, the estimated planes were additionally inclined. To quantify the malrotation, the orientation error was chosen as the angle θ_{pre} between the normal vectors of the planes in the preoperative and contralateral configurations with the angle θ_{post} of the planes in the postoperative and contralateral configurations.

RESULTS

Clinical Results

At the 1-year follow-up, all patients showed a clear improvement in wrist function (Table 2). The range of motion improved on average by 19° of wrist extension, 13° of wrist flexion, 9° of pronation, and 25° of supination compared with their preoperative measurements. On average, the final grip strength improved by 10%. All signs for wrist instability and crepitus were negative. Four patients had no pain according to the pain level classification of Fernandez¹³. Two patients continued to have

moderate (patient 4) or mild (patient 5) pain. Patient 4 had given up her occupation as a waitress because of her limited supination.

Radiological Results

All osteotomies showed radiographic evidence of consolidation at 8 weeks. After 1 year, there was no evidence of degenerative changes, such as joint space narrowing, osteophyte formation, or subchondral sclerosis (grade 0 according to the Jupiter scale¹). The intra-articular step-off was no longer present on the radiographs. According to the system of Knirk and Jupiter¹, the degree of intra-articular incongruity improved from grades 2-3 preoperatively to grade 0 postoperatively. In each case, the measured displacement error d and orientation error θ in the pre- and postoperative configurations are given in Table 3. The intra-articular step-off was significantly reduced ($P < 0.001$, Student paired t-test) by 74% on average. In cases 5 and 6, large errors in the rotational component of the fragments were measured preoperatively. In these cases, the orientation error was reduced by 60% and 77%, respectively. In case 3, the rotational error increased by 8° after the osteotomy.

DISCUSSION

Computer-assisted 3D planning is a well-known method for the exact quantification of malunions¹⁶⁻¹⁸. Similar techniques have been described in spinal surgery²³⁻²⁵, maxillofacial surgery,²⁶ and knee joint arthroplasty²⁷. However, applying the preoperative 3D data at the time of the surgery to correct a malunion can be challenging. Earlier reports described 3D planning approaches in combination with intraoperative guidance, such as aiming devices, for extra-articular distal radius malunions^{20, 21}. Additionally, there is an ongoing prospective randomized controlled trial on the use of patient-specific guides for extra-articular distal radius malunions²². Furthermore, the computer-assisted correction of osteotomies of the radius with rapid prototyped guides has been described in a canine model²⁸.

Only a few studies have described the management of intra-articular distal radius malunions^{5, 7, 8, 14, 15} with or without arthroscopic assistance. This type of injury is technically difficult to treat due to the limited accessibility of the articular surface. In our opinion, extensive opening of the joint capsule to access the joint increases the risk of reducing range of motion due to scarring. Even with direct visualization of the

joint, residual malalignment is common^{15, 19}. Moreover, in the particular situation of addressing a malunited volar Barton fracture, a direct view to the intra-articular step-off is only possible if the volar radiocarpal ligaments are incised or an arthroscopically assisted approach is used. The correction is even more difficult if a fragment needs both shifting and rotating.

As an alternative, the presented technique allows for an extra-articular approach to the intra-articular malunion and obviates the need for the extensive release of the joint capsule and ligaments. In our cases, the smaller fragments, which remained attached to the joint capsule, demonstrated healing and no signs of avascularity. Although the intra-articular step-off was considerably reduced in all cases, malrotation was only noticeably improved in those cases for whom a large rotational error was observed preoperatively. Compared with other studies, we had better¹⁵ or similar⁷ results with respect to the improvement of the articular incongruity and range of motion.

One key benefit of this method is its flexibility as the guides are custom-made. The complexity of the osteotomy may range from a simple single-cut osteotomy, in which the fragment is shifted along the plane, up to multiple, composite osteotomies, in which the fragments are additionally rotated to restore the anatomical position. In particular, the preoperative estimation and intraoperative correction of a rotated fragment is more reliable compared with image intensifier-controlled techniques⁷. Another advantage is that a full-scale print-out of the malunited bone can be produced, providing simulation of the intervention with real surgical tools.

Weaknesses of the presented work include the retrospective design of the study, the small number of patients, the lack of pre- and postoperative outcome or pain level scores, and the absence of a control group. In addition to the complexity of the planning and of the procedure itself, an additional CT scan of the opposite side is required. In our case series, the planning time, including the guide design, ranged from 2 to 4 h. Additional expenses also arise due to manufacturing the patient-specific drill guides, which cost approximately €150–250 (USD 220–320) per case.

A comparative study analyzing guided and conventional intra-articular distal radius osteotomies with respect to accuracy, operation time, and outcome would be worthwhile.

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Figure legends

Figure 1: Preoperative CTs in the posteroanterior (column 1) and sagittal view (column 2) and postoperative CTs in the posteroanterior (column 3) and sagittal view (column 4) are given for each patient.

Figure 2: The results of the computer-assisted planning are given for each patient. Column 1: Preoperative radius (brown) with a drill guide model. Column 2: Fragment(s) before (violet) and after (green) the planned correction. Column 3: Fragment(s) in the planned position (green) superimposed on the actual postoperative result.

Figure 3: An example of the quantification of the step-off in 3D. (a) A surface patch (denoted by red dots) is selected on the articular surface of the preoperative radius. The best-fitting 3D plane, shown in orange, is calculated based on the selected points. (b) The same procedure is performed for the superimposed contralateral radius (green dots and green plane). (c) The step-off is estimated by measuring the average distance between the planes.